

# Impact of the Fan Design and Rotational Direction on the Thermal Characteristics of Induction Motors

Goh, S., Fawzal, A. S., Gyftakis, K. N. & Cardoso, A. J. M

Author post-print (accepted) deposited by Coventry University's Repository

## Original citation & hyperlink:

Goh, S, Fawzal, AS, Gyftakis, KN & Cardoso, AJM 2018, Impact of the Fan Design and Rotational Direction on the Thermal Characteristics of Induction Motors. in 2018 XIII International Conference on Electrical Machines (ICEM). IEEE, pp. 1227-1233, XXIII International Conference on Electrical Machines, Alexandroupoli, Greece, 3/09/18.

<https://dx.doi.org/10.1109/ICELMACH.2018.8506974>

DOI 10.1109/ICELMACH.2018.8506974

Publisher: IEEE

**© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.**

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

# Impact of the Fan Design and Rotational Direction on the Thermal Characteristics of Induction Motors

S. Y. Goh, A. S. Fawzal, K. N. Gyftakis and A. J. M. Cardoso

**Abstract** – Low manufacturing cost and high reliability make the induction machine suitable for different constant and variable speed applications. For machines operating in hazardous environments, the fully enclosed type is used, with limited access to the stator and rotor. Indirect air cooling method is usually employed with fins casing and an attached fan. Thus, the fan design is crucial as being the only resource to remove heat away from the machine. A poor thermal management of the electrical machine can lead to a machine failure and reduce the machine lifespan. Some machines are operating for bi-directional operation, which means the performance of the machine should be reviewed under both conditions. This paper focus on the impact of the fan cooling on the thermal profile of a 5.5 kW induction machine under bi-directional operation. Comparative studies using CFD simulations have been carried out to identify the effect of different fan types when operating at particular conditions. The performed work provides an understanding of the air flow under bi-directional operation, which notes the importance of the fan design and rotational direction in induction machines.

**Index Terms**—Computational fluid dynamics (CFD), Cooling, Fan design, Induction machine, Thermal management.

## I. INTRODUCTION

INDUCTION machines have a long history and have been widely used in different applications. Throughout the years, many research works have been accomplished on different aspects such as; material selection, winding design, stator/rotor teeth's shape, cooling methods, etc. [1]-[3]. However, the limitation of the computational power in the past, which resulted in lengthy computational time constraints, led to reduction of the complexity of the models that could be studied. As a result, several aspects of the induction motor operation have never been fully studied and analysed.

The performance of an electrical machine greatly relies on the design of the magnetic circuit and the thermal characteristics of the machine during operation. The studies of electromagnetic and thermal analysis are equally important at the design stage of a machine [1]. Losses originating from the stator such as the copper and iron ones are the main contributors to the heat generation in the electric machine. In

collaboration with the rotor losses, the machine's operating temperature rises. That temperature increase leads to the changes of the machine's material properties such as the electrical resistivity of conductors, which may affect the magnetic field strength and consequently the magnetic flux density. Other material properties, such as the dielectric permittivity of the insulation materials are reduced while this degradation will accelerate when the machine is operating under high temperatures for long term [4]-[5]. According to the report from Motor Reliability Working Group, most of the stator failures are due to the winding insulation breakdown and overheating [6]. To avoid an unexpected machine failure before the end of its life, operation below the allowable maximum operating temperature is not sufficient. A more precise prediction of the machine performance and an in-depth thermal study of the machine are crucial in elongating the machine life.

As mentioned before, the heat affects the machine performance and shortens the components lifetime. The thermal management is about balancing between the generation and removal rate of heat from the system [7]. An optimal thermal management of the electric machine allows to maintain the machine temperature below the maximum temperature within the rated speed and torque range. Even though several cooling solutions have been proposed, which are efficient in heat removing, however they have not been designed for cost efficient manufacturability [8]-[9]. Thus, considering the manufacturing cost, most of the conventional induction machines are fan cooled type machines.

For a Totally Enclosed Fan Cooled (TEFC) induction machine, there is no air circulation between the inner and external parts of the machine while it is protected from dirt and moisture from the environment. Thus, this type of machine is suitable for industrial applications. Since the TEFC induction machine is sealed, the attached fan at the rear shaft of the machine plays the significant role of drawing the air surrounding the motor casing and carry the heat away from the machine [10]-[11]. The fan design and type can affect the air flow characteristics for this particular machine which eventually has an impact on the machine's thermal profile. To improve the heat transfer rate, the motor housing is usually designed with fins to elongate the surface area for improved heat convection.

Inside the TEFC machine, the heat is dissipated from the inner to the frame through conduction and convection. The amount of the airflow through the fins determines the efficiency of the external air cooling. Several studies have been carried out to optimize the fin design for electrical machines by observing the axial air velocity and heat transfer coefficient across the frame [12]-[14]. The cooling air speed

---

This work was partially supported by the Portuguese Foundation for Science and Technology (FCT) under Project UID/EEA/04131/2013S.

Y. Goh and A. S. Fawzal are with the Faculty of Engineering, Environment, and Computing, Coventry University, Coventry CV1 5FB, U.K. (email: ac7199@coventry.ac.uk, fawzala@uni.coventry.ac.uk).

K. N. Gyftakis is with the School of Computing, Electronics, and Mathematics (CEM) and the Research Institute for Future Transport and Cities, Coventry University, Coventry CV1 5FB, U.K. (e-mail: k.n.gyftakis@ieee.org).

A. J. Marques Cardoso is with the CISE – Electromechatronic Systems Research Centre, Universidade da Beira Interior, Calçada Fonte do Lameiro, P – 6201-001 Covilhã, Portugal (e-mail: ajmcardoso@ieee.org).

is varying with the fan, fan cowl and fin design. Apart from these, the rotational speed is also one of the main factors affecting the air velocity [15].

There are several methods to evaluate the heat transfer of electrical machines such as the Lumped Parameter (LP) method, the Finite Element Analysis (FEA) and the Computational Fluid Dynamics (CFD). In the electrical machine design field, the LP network is a commonly used method preferred for its lower computational time compared to the FEA and CFD approaches. However, the FEA and CFD are more suitable for in-depth analysis [16]-[19].

The purpose of this paper is to investigate the effect of the fan type and the rotating direction on the thermal characteristics of TEFC induction machines by using the CFD approach.

## II. THERMAL CHARACTERISTICS OF THE INDUCTION MACHINE

A 5.5 kW 3-phase TEFC induction machine, that has been designed to operate bi-directionally, has been used in this study. This machine was initially studied experimentally and some data were collected and used for comparing and setting up for the simulation analysis. The geometrical model was formed based on the actual machine structure and the manufacturer blueprints, while the flow characteristic studies were carried out using the Star CCM+ v12.04 software.

### A. Stator

The stator core with 36 slots is pressed fit into the machine housing. The generated heat from the conductors is transferred to the housing through the stator core (high temperature to low temperature). In [20], it was mentioned that the main direction of the heat flow is from the centre of stator slot to the stator laminate. The heat flow path is greatly affected by the barriers such as the air gap, the slot liner, the resin within the voids of the conductors and the impregnation goodness [20]-[21].

However, these barriers become important when the stator slots are studied in detail. For a complex geometry such as the one presented in this paper, these barriers have less impact to the overall changes of the machine temperature profile due to the fan design and rotating direction. Thus, in the section of stator, the stator slot is simplified and filled with copper bulk.

### B. Rotor

The aluminium squirrel cage rotor for this machine is designed with 10 degrees of skew angle and an air gap of 0.12 mm between the rotor and stator. A part of the rotor losses is conducted through the shaft and the interior rotating air flow.

The interior air flow can be divided into three areas; air gap, front and end spaces. The heat transfer within the tight air gap is a critical aspect in an electrical machine and is challenging in terms of modelling and experimental investigation [22]-[23]. For radial flux machines, the air gap flow is related to the study of Taylor vortices. Recirculation and instability of the flows within the air gap contribute to the formation of the Taylor vortices that have an effect on the

temperature [24]-[27]. However, the Taylor vortices rely on the rotating speed of the rotor.

To circulate the interior airflow and create air swirling during rotating, wedge features are on the end rings of the rotor. The flow circulation is to remove heat from rotor, also from the end winding to the housing wall through heat convection [28]-[29]. However, the air conduction may dominate in the heat transfer rather than the convection at low rotating speeds. This is because the flow is more localized around the components without any air movement in the machine.

### C. Fan Design

The electric motor is attached with a 12 radial blades fan at the end of the shaft, while usually the number of blades for fan is between 8 and 12. The fan of TEFC induction machines is not designed specifically as an axial fan. It is derived from a centrifugal fan but with a combination of a fan cowl, the flow changes from radial to axial direction. It is common to find a radial blades fan in such motors as this design has the same flow performance in bi-directional operation. Radial blades fan option is robust as the straight fan feature does not collect dirt, high durability and easy to repair. However, this fan design is known to have low fan efficiency. Therefore, the study begins with assessing a radial fan as a reference (Fig. 1).

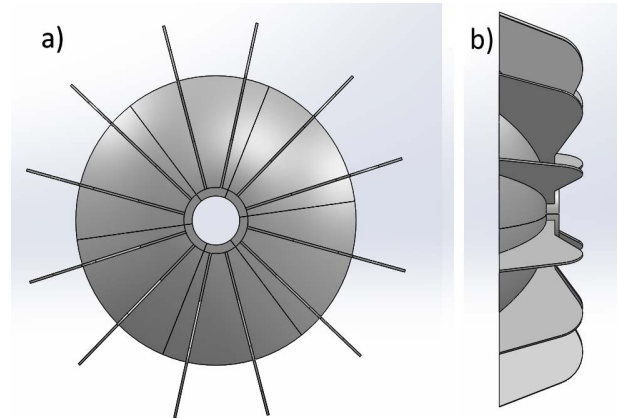


Fig. 1. Fan with radial blades: (a) front and (b) side view.

On the other hand, a curved blades fan produces better flow performance compared to the radial blades one. It is depending on its velocity vector of the fan blade tip. For instance, when the curve fan in Fig. 2 is designed to rotate in clockwise direction, it is called ‘backward curved’ fan; while if the same fan design rotates in counter-clockwise direction, the fan now becomes ‘forward curved’ fan. Depending on the way the fan is driven the flow changes and as a result the two curved blades fan cases have different characteristics. Thus, a TEFC motor with curved blades fan is usually designed for uni-directional operation in order to keep its cooling performance as specified by the manufacturer. Here, for comparative purposes, the curved blades fan is simulated in clockwise and counter-clockwise directions and compared also with the radial blades fan case.

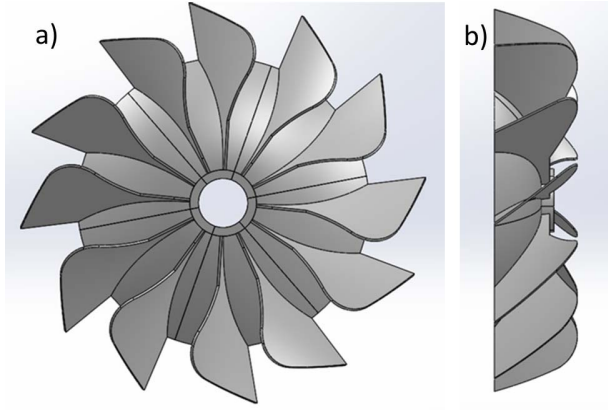


Fig. 2. Fan with curved blades: (a) front and (b) side view.

Regarding the fan design, several key parameters would affect the performance; blade geometry, blade angle, inlet-outlet radius ratio and number of blades [7], [30]-[31]. The curvature of the leading edge and blade tip is to form an airfoil shape that will lead the air velocity to increase from the edge to the tip. Other parameters are the number of blades and the blades' width that define the total air volume [31]. For this model, the material properties of fan and other components are listed in Table I.

TABLE I  
MATERIAL PROPERTIES OF DIFFERENT COMPONENTS

PARTS	MATERIAL	THERMAL CONDUCTIVITY [(W / M K)]
STATOR AND ROTOR CORE	IRON	37
CONDUCTORS	COPPER	398
ROTOR CAGE	201.0-T7 ALUM	121
FRAME AND FAN COWL	GRAY CAST IRON	45
SHAFT	AISI 1045 STEEL	49.8
FAN	POLYPROPYLENE	0.17
AIR		0.02603

#### D. Simulation Set-up

For the modelling set-up, the 1/6 of the induction motor is being studied (Fig. 3-a) and this is sufficient to represent the overall machine behaviour. To avoid any reverse flow, the fluid domain is extended radially 2 times the motor radius and axially (front and end of the machine) with 1.5 of the electric motor length (Fig. 3-b) This enables the external air

to move around freely. The model was set with the conditions listed in Table II. The electrical machine runs at a constant rotating speed of 1440rpm under full load condition with initial and ambient temperature of 26°C. The total losses have been obtained from experimental testing. Since the 1/6 of the machine is used, only 1/6 of the total losses will be applied in the studies.

TABLE II  
INITIAL CONDITION FOR ALL SIMULATIONS

Initial Condition	Value
Rotating Speed (rpm)	1440
Initial Temperature (°C)	26
Ambient Temperature (°C)	26
Total Losses (W)	
Rotor	0.8154
Rotor Cage	61.7
Stator	55.8
Winding	171.1

The fluid region is divided into three sub-regions; interior, rotating fan and exterior. All the regions include solid parts which were meshed with parameters shown in the first column of Table III apart from the air gap between stator and rotor. The total mesh for the model consists of 4.5 million cells (Fig. 4).

The moving parts such as the rotor iron core, the rotor cage, the shaft and the fan were set to rotate with speed 1440 rpm. The same rotational speed is applied to the rotating region of the fan and the moving reference frame of the interior air. All the sectioned walls were defined as symmetry wall while the far wall of external air was set as open boundary (stagnation inlet).

TABLE III  
MESHING PARAMETERS

	Major Parts	Rotor-Stator Gap
<u>Global</u>		
Min (mm)	1	0.05
Max (mm)	10	0.2
<u>Prism</u>		
Thickness (mm)	3	0.8
Number	5	3
Stretching	1.5	1.1

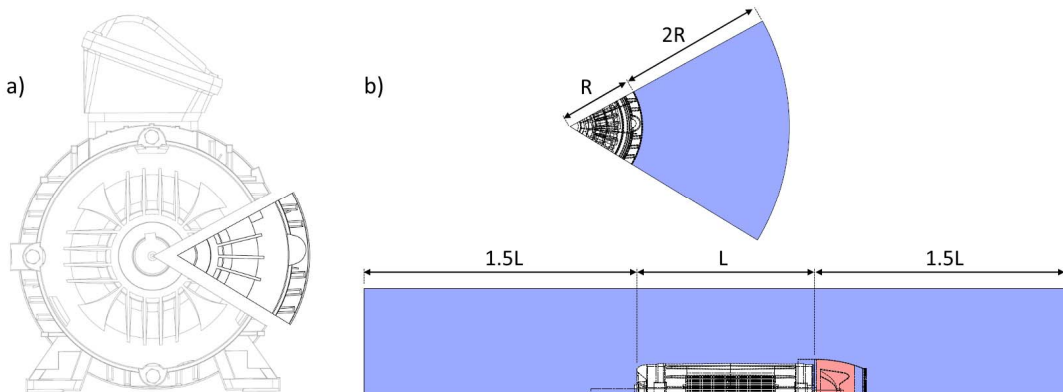


Fig. 3. Model set-up for the machine: (a) 1/6 of the machine and (b) the CFD model in side and top view including the fluid domain.



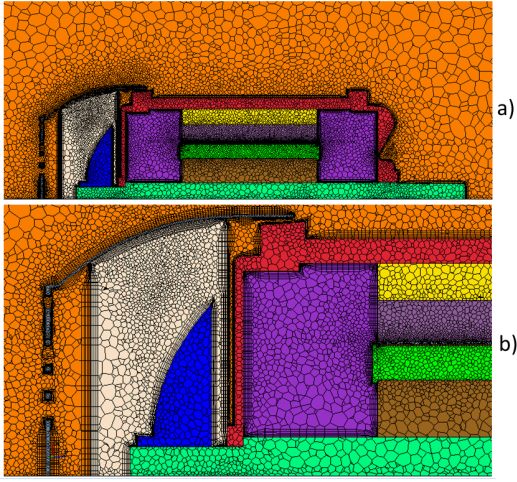


Fig. 4. Meshing for the CFD model in (a) whole machine and (b) detailed view.

### III. RESULTS AND DISCUSSION

The blade curvature and the direction of the fan rotation define the flow pattern within the rotating region. This affects the exiting air velocity speed from the rotating region and the air movement near to the frame, consequently affecting the heat transfer rate from the frame surface to the air.

#### A. The Radial Blades Case

Fig. 5 shows the velocity profile of the radial blade fan at 1440 rpm. The air is entering the rotating region through the opening fan cowl and the mesh design enhances the flow speed as in the figure. The speed and pressure difference between the rotating region and inlet cause a circulation flow. However, an obvious air movement is observed within the rotating region. The end tip of the blade drives the air to the frame. The elongated length of fan cowl guides the cold air to flow over the machine. As a combination between the fan design and the fan cowl, the air flow exits from the rotating region with higher speed.

The windage losses or power consumption for radial blades fan is 4.79W.

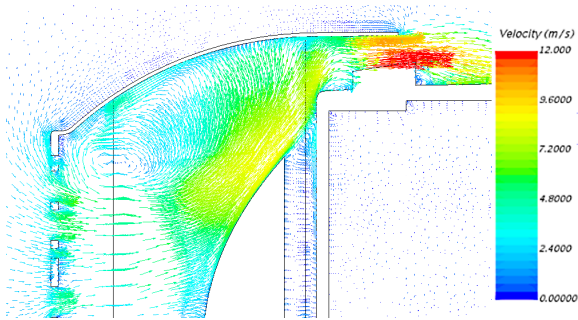


Fig. 5. Velocity profile of radial blade fan.

#### B. The Curved Blades Case

Compared to the radial blades case, there are multiple small circulations existing in the rotating region with curved blades fan when rotate in clockwise direction. These circulations concentrated at the region close to the fan cowl wall. The sudden change of the near wall air velocity and the high air speed near to the rotating region creates a flow separation, which forms flow circulations in those regions.

Unlike the radial blades case, most of the flow is driven near to root of the fan blade as shown in Fig. 6. However, similar to the radial blades fan, the exit air velocity is quite strong and approximately 12m/s.

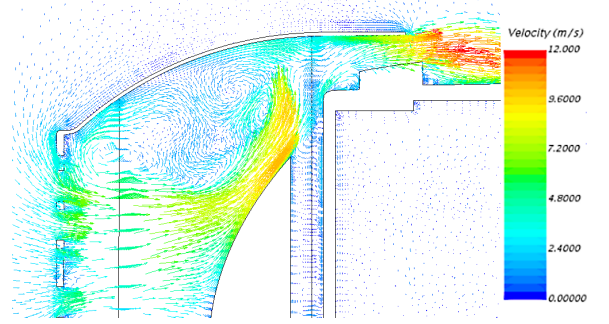


Fig. 6. Velocity profile of curve blade fan in clockwise direction.

To get a better understanding, the fan is also set to rotate in counter-clockwise (CCW) direction. It was found that multiple small circulations exist but with slightly higher velocity compared to the clockwise rotating curved blades fan (Fig. 7). Similarly to the previous study, most of the flow is drawn near to the root of the fan blade. However, the flow exits with lower velocity.

The windage losses for curved blades fan of clockwise and counter-clockwise rotating direction are 4.80W and 6.19W respectively.

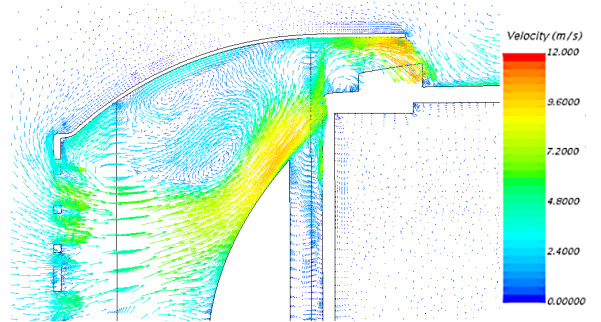


Fig. 7. Velocity profile of curve blade fan in counter-clockwise direction.

#### C. Temperature Profile

The flow characteristic of the fan has an impact on the cooling effect of the electrical machine. This can be observed from the temperature changes across the length of the machine components. As illustrated in Fig. 8, the components temperature such as machine cover, stator, winding, rotor etc. have been captured along the length of each machine parts.

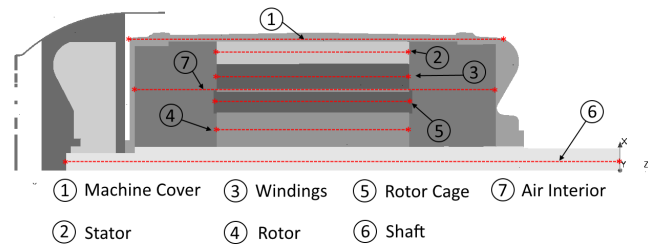


Fig. 8. Temperature measurement of different machine components.

Regardless to the fan type and rotating direction, the temperature of the machine cover is consistent and increases drastically for the first 60 mm from the fan. However, the effect of the fan type and flow direction becomes significant at where the stator and rotor are located. This can be seen from the machine cover temperature between the 60 mm to 180 mm. The temperature increase to 58°C with counterclockwise rotating curved blade while for radial fan, the frame temperature is 55 °C. With clockwise curved blades fan, the frame temperature is around 52 °C.

The main heat source of this machine is the copper losses and this heat is conducted away by the stator and the machine frame. This can be seen in Fig. 9 and Fig. 10 where the machine frame temperature is approximately the same as the stator temperature. Even though, copper conductors are located within a small slot area, however, the temperature difference between the stator and winding is only about 2 °C. This shows that heat has transferred to the stator and the frame and reaches an equilibrium condition.

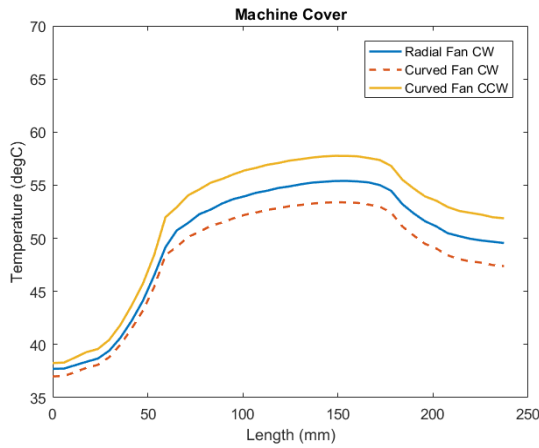


Fig. 9. Temperature profile of the machine cover.

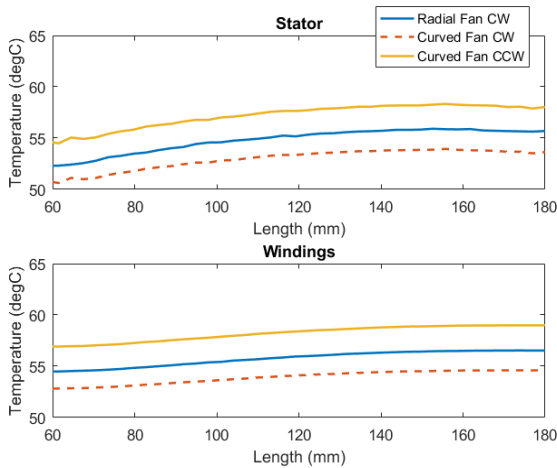


Fig. 10. Temperature of stator and winding.

The results also show that the temperature increases slightly along the components length. However, this is not the same case as in the rotor (Fig. 11). This is because the velocity of the external cold air flow reduces axially across the frame and the temperature increases gradually as the flow is carrying more heat. In the rotor, the tight air gap reacts as a thin layer of air insulation between the stator and rotor during

operation. Without any interchange of hot air with the exterior cold air, the temperature across seems to be more consistent (Fig. 11-a and b). This also explains the reason why the rotor temperature is much higher than the stator.

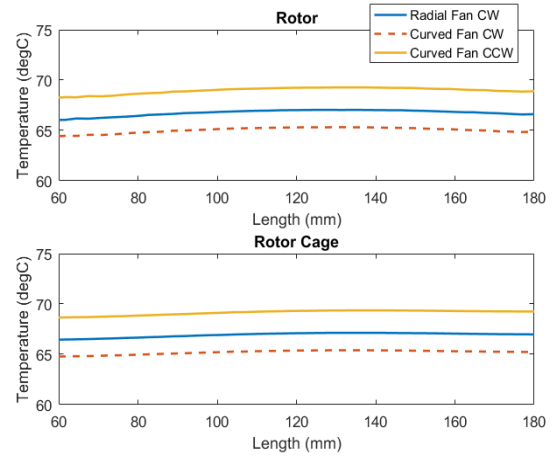


Fig. 11. Location of temperature measurement of different machine components.

As the TEFC is a sealed machine without any air circulation with external flow, the hot air retains in the machine. The limitation of the air flow path in the system restricts the amount of heat that can be carried away from the air gap and be dissipated to the housing wall. Thus, the air temperature within 60-180 mm has higher temperature with a sharp increase of 20°C (Fig. 12) and is maintained constant along the length. Similar trends can be found in either with radial or curved blades fan.

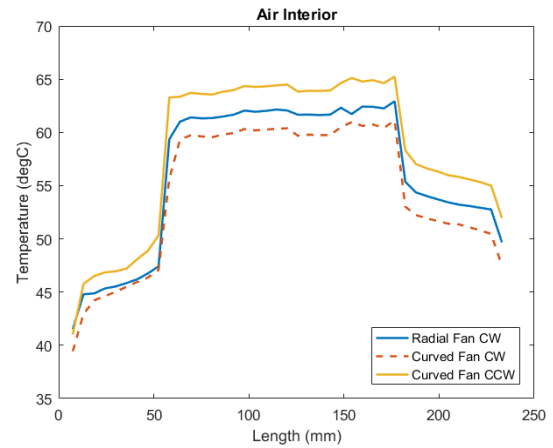


Fig. 12. Air temperature in the electric machine

The rotating direction of the radial blades fan does not affect the temperature profile of the machine because the fan profile is the same in both directions. However, for the curve blades fan, the rotating direction has a direct impact to the machine temperature and at this particular condition, it is observed that the temperature difference is about 4-5 °C. These differences may become more noticeable with greater machine losses occurring at higher loads.

This difference is also revealed in the shaft temperature (60 mm-300 mm) as in Fig. 13. For a bi-directional machine, the fan reacts as the backward-curved blades one when it rotates clockwise and as a forward-curved bladed one for

counter-clockwise operation. The backward-curved blades case has better efficiency than the forward-curved blades because of the greater air flow capacity. A comparison between the studied cases reveals that, the radial blades case behaviour is between the forward and backward curved blades cases while its occurring temperature is the average temperature between the forward and backward curved blades cases as well (Fig. 9 – Fig. 13).

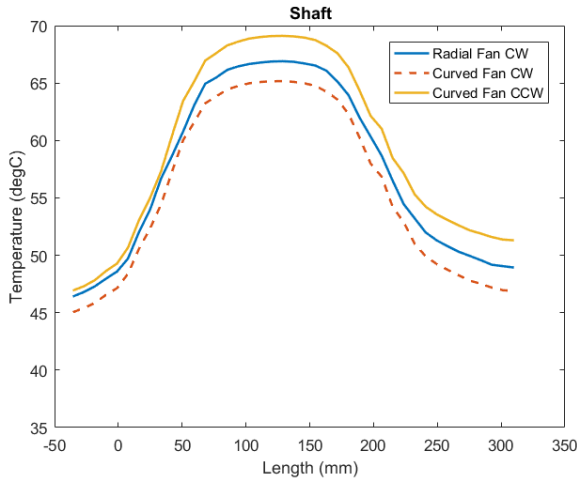


Fig. 13. Shaft temperature along the length.

#### IV. CONCLUSIONS

The fan blade design and machine rotating direction affect the heat transfer rate from the machine frame. In clockwise direction, the curved blades case is more efficient in removing heat than the radial blade and vice versa when in counter-clockwise rotation. This is displayed in the temperature profile of the machine components and the inner air temperature.

Since the geometry of both radial and curved blades was the same, the variation of the blade angle is the only factor that might accelerate the radial outward air velocity. The greater the air flow velocity the more efficient the heat transfer. However, this will require further investigation as the air changes of the blade angle also affects the air capacity delivery.

#### V. REFERENCES

- [1] G. Bramerdorfer, J. Tapia, J. Pyrhonen and A. Cavagnino, "Modern electrical machine design optimization: techniques, trends, and best practices," *IEEE Trans. Ind. Electr.*, 2018, early access.
- [2] M. Y. Mohamed, S. A. A. Maksoud, M. Fawzi, and A. E. Kalas, "Effect of poles, slots, phases number and stack length changes on the optimal design of induction motor," in *2017 19th International Middle East Power Systems Conf. (MEPCON)*, 2017, pp. 466-471.
- [3] A. Mishra, B. Rajpurohit and R. Kumar, "Induction machine drive design for enhanced torque profile," *IEEE Trans. Ind. Appl.*, 2017, early access.
- [4] K. Gyftakis, M. Sumislawska, D. Kavanagh, D. Howey and M. McCulloch, "Dielectric characteristics of electric vehicle traction motor winding insulation under thermal ageing," *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1398-1402, 2016.
- [5] M. Sumislawska, K. Gyftakis, D. Kavanagh, M. McCulloch, K. Burnham and D. Howey, "The impact of thermal degradation on properties of electrical machine winding insulation material," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 2951-2960, 2016.

- [6] Motor Reliability Working Group, "Report of large motor reliability survey of industrial and commercial installations, Part I," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 853-864, 1985.
- [7] A. S. Fawzal, R. M. Cirstea, K. N. Gyftakis, T. J. Woolmer, M. Dickson, and M. Blundell "Fan performance analysis for rotor cooling of axial flux permanent magnet machines," *IEEE Trans. Ind. Appl.*, vol. 53, no.4, pp. 3295-3304, 2017.
- [8] J. Potgieter, F. Marquez-Fernandez, A. Fraser and M. McCulloch, "Performance evaluation of a high speed segmented rotor axial flux switched reluctance traction motor," in *2016 XXII International Conf. on Electrical Machines (ICEM)*, 2016, pp. 531-537.
- [9] P. Lindh, I. Petrov, A. Jaatinen-Varri, A. Gronman, M. Martinez-Iturralde, M. Satrustegui and J. Pyrhonen, "Direct liquid cooling method verified with an axial-flux permanent-magnet traction machine prototype," *IEEE Trans. Ind. Elec.*, vol. 64, no. 8, pp. 6086-6095, 2017.
- [10] A. Naskar and D. Sarkar, "Numerical analysis of three dimensional steady state heat conduction in the rotor of an induction motor by finite element method," in *Proc. of The 2014 International Conf. on Control, Instrumentation, Energy and Communication (CIEC)*, 2014, pp. 686-690.
- [11] B. Dutta and S. Chowdhury, "Steady state thermal model of TEFC induction machine," in *2012 IEEE International Conf. on Power Electronics, Drives and Energy Systems (PEDES)*, 2012, pp 1-6.
- [12] S. Ulbrich, J. Kopte, and J. Proske, "Cooling fin optimization on a TEFC electrical machine housing using a 2-D conjugate heat transfer model," *IEEE Trans. Ind. Elec.*, vol. 65, no. 2, pp. 1711-1718, 2018.
- [13] S. H. Moon, Y.H. Jung, and K.W Kim, "Numerical investigation on thermal-flow characteristics of a totally enclosed fan cooled induction motor," *2016 XXII International Conf. on Electrical Machines (ICEM)*, 2016, pp. 1928-1935.
- [14] M. A. Valenzuela and J. A. Tapia, "Heat transfer and thermal design of finned frames for TEFC variable-speed motors," *IEEE Trans. Ind. Elec.*, vol. 55, no. 10, pp. 3500-3508, 2008.
- [15] A. Boglietti, A. Cavagnino, and D. A. Staton, "TEFC induction motors thermal models: a parameter sensitivity analysis," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 756-763, 2005.
- [16] C. Kral, A. Haumer, M. Haigis, H. Lang and H. Kapeller, "Comparison of a CFD analysis and a thermal equivalent circuit model of a TEFC induction machine with measurements," *IEEE Trans. Energy Conv.*, vol. 24, no. 4, pp. 809-818.
- [17] F. Ahmed, E. Ghosh and N. Kar, "Transient thermal analysis of a copper rotor induction motor using a lumped parameter temperature network model," in *2016 IEEE Transportation Electrification Conf. and Expo (ITEC)*, 2016, pp.1-6.
- [18] D. Nair, T. Jokinen and A. Arkkio, "Coupled analytical and 3D numerical thermal analysis of a TEFC induction motor," *2015 18th International Conf. on Electrical Machines and Systems (ICEMS)*, Oct. 2015, pp.103-108.
- [19] E. Schmidt, J. Buschbeck and M. Vogelsberger, "Multi-physics optimization of air-cooled asynchronous induction machines for railway traction drives," in *2017 20th International Conf. on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-6.
- [20] A. Boglietti, A. Cavagnino, and D. Staton "Determination of critical parameters in electric machine thermal models," *IEEE Trans. Ind. Appl.*, vol.44, no.4, pp. 1150-1159, 2008.
- [21] S. Y. Goh, J. Wale, and D. Greenwood, "Thermal analysis for stator slot of permanent magnet machine," in *2016 XXII International Conf. on Electrical Machines (ICEM)*, 2016, pp. 2093-2098.
- [22] D. Howey, A. Holmes and K. Pullen, "Measurement and CFD prediction of heat transfer in air-cooled disc-type electrical machines," *IEEE Trans. Ind. Appl.*, vol. 47, no. 4, pp. 1716-1723, 2011.
- [23] D. A. Howey, A. S. Holmes and K. R. Pullen, "Prediction and measurement of heat transfer in air-cooled disc type electrical machine," *5th IET Int. Conf. on Power Electronics, Machines and Drives (PEMD 2010)*, 2010, pp. 1-6.
- [24] D. A. Howey, P. R. N. Childs, and A. S. Holmes, "Air-gap convection in rotating electrical machine," *IEEE Trans. Ind. Elec.*, vol. 59, no. 3, pp. 1367-1375, 2012.
- [25] P. Romanazzi, and D. A. Howey "Air-gap convection in a switched reluctance machine," in *Tenth Int. Conf. on Ecological Vehicles and Renewable Energies (EVER)*, 2015, pp. 1-7.
- [26] M. Hosain, R. Fdhila and K. Rönnerberg, "Air-gap flow and thermal analysis of rotating machines using CFD," *Energy Procedia*, vol. 105, pp. 5153-5159, 2017.

- [27] G. Friedrich, S. Vivier, R. Khliissa, and B. Assaad, "Determination of rotor-stator heat exchange coefficients in the case of totally enclosed machines: application to an integrated stator-generator," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013, pp. 1526-1533.
- [28] W. Tong, *Mechanical design of electric motors*. Boca Raton, FL: CRC Press, 2014, pp. 409-477.
- [29] F. Ahmed and N.C. Kar, "Analysis of end-winding thermal effects in a totally enclosed fan-cooled induction motor with a die cast copper rotor," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 3098-3109, 2017.
- [30] T. Jercic, D. Zarko, M. Martinovic, M. Kovacic, J. Juric, Z. Hanic, and S. Stipetic, "Centrifugal fan design for permanent magnet synchronous motor in a traction application," in *2017 IEEE Int. Electr. Machines and Drives Conf.*, 2017, pp. 1-7.
- [31] F. Bleier, *Fan handbook*. New York: McGraw-Hill, 1998, pp. 7.1-7.58.

## VI. BIOGRAPHIES

**Siew Yan Goh** was born in Selangor, Malaysia. She received MSc in Engineering Design from Liverpool John Moores University in 2008. She pursued her PhD in the same institution in the area of roundness monitoring for cylindrical grinding machine (2013). Then, she worked as KTP associate for the axial flux electric machine cooling methods and electric machine design at Oxford Brookes University and YASA Motors Ltd (2013 - 2015). She was Post-Doctoral Research Fellow in Warwick Manufacturing Group (WMG), University of Warwick (2015-2017) for HVEMS project. She is currently an Assistant Lecturer with the School of Mechanical, Aerospace and Automotive Engineering, Faculty of Engineering, Environment and Computing, Coventry, U.K. Her research interests are mainly in thermal management and cooling of electric machine, design and manufacturing.

**Ahmad Syahid Fawzal** was born in Selangor, Malaysia, on November 1982. He received the Diploma of Engineering Technology degree in machine building and maintenance from Universiti Kuala Lumpur Malaysia France Institute, Selangor, Malaysia, in 2007; the B.Eng. degree in mechanical engineering from the University of Derby, U.K., in 2009; and the M.Sc. degree in computational fluid dynamics from Cranfield University, U.K., in 2012. He is currently working toward the Ph.D. degree at Coventry University, U.K sponsored by YASA Ltd., Oxford, UK. His employment has included computational fluid dynamics (CFD) Project Engineer at BMT Fluid Mechanics Ltd., London, U.K., and Kuala Lumpur,

Malaysia, and also was a Machine Reliability Consultant (vibration) at AF Condition Monitoring (M) Sdn Bhd., Kuala Lumpur. His research interests include windage losses, fan performance, and thermal and cooling of electrical machines.

**Konstantinos N. Gyftakis** was born in Patras, Greece, in May 1984. He received the Diploma in Electrical and Computer Engineering from the University of Patras, Patras, Greece in 2010. He pursued a PhD in the same institution in the area of electrical machines condition monitoring and fault diagnosis (2010-2014). Then he worked as a Post-Doctoral Research Assistant in the Dept. of Engineering Science, University of Oxford, UK (2014-2015).

Since 2015 he has been a Lecturer on Electrical and Electronic Engineering, School of Computing, Electronics and Mathematics, Faculty of Engineering, Environment and Computing, Coventry University, UK. He is also an Associate Member of the Institute for Future Transport and Cities, Coventry, UK and a Member of the "Centro de Investigação em Sistemas Electromecatrónicos" (CISE), Portugal.

His research interests focus in the fault diagnosis, condition monitoring and degradation of electrical machines. He has authored/co-authored more than 60 papers in International scientific journals and conferences.

**Antonio J. Marques Cardoso** received the Dipl. Eng., Dr. Eng., and Habilitation degrees from the University of Coimbra, Coimbra, Portugal, in 1985, 1995 and 2008, respectively, all in Electrical Engineering. From 1985 until 2011 he was with the University of Coimbra, Coimbra, Portugal, where he was Director of the Electrical Machines Laboratory. Since 2011 he has been with the University of Beira Interior (UBI), Covilhã, Portugal, where he is Full Professor at the Department of Electromechanical Engineering and Director of CISE - Electromechatronic Systems Research Centre (<http://cise.ubi.pt>). He was Vice-Rector of UBI (2013-2014). His current research interests are in fault diagnosis and fault tolerance in electrical machines, power electronics and drives. He is the author of a book entitled *Fault Diagnosis in Three-Phase Induction Motors* (Coimbra, Portugal: Coimbra Editora, 1991), (in Portuguese) and of around 400 papers published in technical journals and conference proceedings. He currently serves as Associate Editor for the *IEEE Transactions on Industry Applications*, *IEEE Transactions on Industrial Electronics*, *IEEE Transactions on Power Electronics*, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, and also for the *Springer International Journal of Systems Assurance Engineering and Management*.